

Review on latest progress on Supergiant Fast X-ray Transients and future direction

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Abstract

In the recent years, the discovery of a new class of Galactic transients with fast and bright flaring X-ray activity, the Supergiant Fast X-ray Transients, has completely changed our view and comprehension of massive X-ray binaries. These objects display X-ray outbursts which are difficult to be explained in the framework of standard theories for the accretion of matter onto compact objects, and could represent a dominant population of X-ray binaries. I will review their main observational properties (neutron star magnetic field, orbital and spin period, long term behavior, duty cycle, quiescence and outburst emission), which pose serious problems to the main mechanisms recently proposed to explain their X-ray behaviour. I will discuss both present results and future perspectives with the next generation of X-ray telescopes.

Key words: X-ray binaries, X-ray sources, accretion and accretion disks, supergiants

1 Main observational properties of a new sub-class of High Mass X-ray Binaries: the Supergiant Fast X-ray Transients

High Mass X-ray Binaries (HMXBs) contain a compact object (a neutron star or a black hole) accreting matter from a massive companion star. They can be divided into three different sub-classes, depending on both the donor type (OB supergiant or Be star) and the X-ray activity (persistent or transient): (1)-supergiant HMXBs with persistent emission (divided into (1a)-wind-fed and (1b)-disk-fed accretors), (2)-Be/X-ray transients (although there are also

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a few Be/X-ray binaries with persistent low luminosity X-ray emission) and, more recently, the **(3)**- supergiant HMXBs with fast transient emission, the so-called Supergiant Fast X-ray Transients (SFXTs). Liu et al. (2006) list 114 HMXBs located in our Galaxy, 66 of which are classified as accreting X-ray pulsars. Most of them are in binaries with Be stars, although the number of HMXBs with supergiant companions is continuously growing thanks to the *INTEGRAL* discoveries in the energy range 17–100 keV: indeed, about 70% of the HMXBs discovered with *INTEGRAL* host OB supergiants (Bird et al. 2010).

SFXTs are hard X-ray transients displaying a high dynamic range of $\sim 10^3$ – 10^5 , with sporadic, recurrent, bright and short (a few hour long) flares (Sguera et al. 2005, 2006; Negueruela et al. 2006a), reaching 10^{36} – 10^{37} erg s $^{-1}$. This fast flaring activity is superimposed on outburst phases lasting a few days, shorter than those displayed by Be/X-ray transients (Romano et al. 2007; Sidoli et al. 2009; Rampy et al. 2009). Their optical association with blue supergiants has led to the identification of ten members (e.g. Halpern et al. 2004, Pellizza et al. 2006, Masetti et al. 2006, Negueruela et al. 2006b, Nespoli et al. 2008), together with several candidates with fast hard X-ray flaring activity but still unknown optical/IR counterparts.

Their long term properties (on timescales of months) consist of a large flux variability at an average intermediate X-ray luminosity of 10^{33} – 10^{34} erg s $^{-1}$ (Sidoli et al. 2008), between the quiescence and the flare peaks. The lowest luminosity level detected in a few SFXTs, 10^{32} erg s $^{-1}$, sometimes shows a very soft spectrum (and, likely, no accretion; e.g. in IGR J17544–2619, in’t Zand 2005), sometimes a harder X-ray emission together with mild flux variability (indicative of ongoing accretion at a very low level, e.g. IGR J08408–4503, Sidoli et al. 2010). A common property of accreting pulsars in HMXBs is the X-ray spectral shape, typically characterized by a flat hard power law below 10 keV (photon index ~ 0 –1), together with a high energy cut-off in the range 10–30 keV, sometimes strongly absorbed at soft energies (Walter et al., 2006). SFXTs display a similar spectral shape when they are in outburst, thus it is usually assumed that most of these sources harbour neutron stars, although X-ray pulsations have been detected *only* in about half of them (5 of about 10 members of the class) with spin periods ranging from 4.7 s (AX J1841.0–0536, Bamba et al. 2001) to 228 s (IGRJ 16465–4507, Lutovinov et al. 2005) and 1246 s (for the SFXT candidate IGRJ 16418–4532, Walter et al. 2006). The possibility of the presence of a black hole in non-pulsating SFXTs cannot be completely ruled out.

SFXTs orbital periods have been determined in 8 sources, spanning a large range as well, between 3.3 days (IGRJ 16479–4514; Jain et al. 2009) and 165 days (IGRJ 11215–5952; Sidoli et al. 2006, 2007; Romano et al. 2009). The SFXTs for which both the orbital and spin periods are known can be overplot-

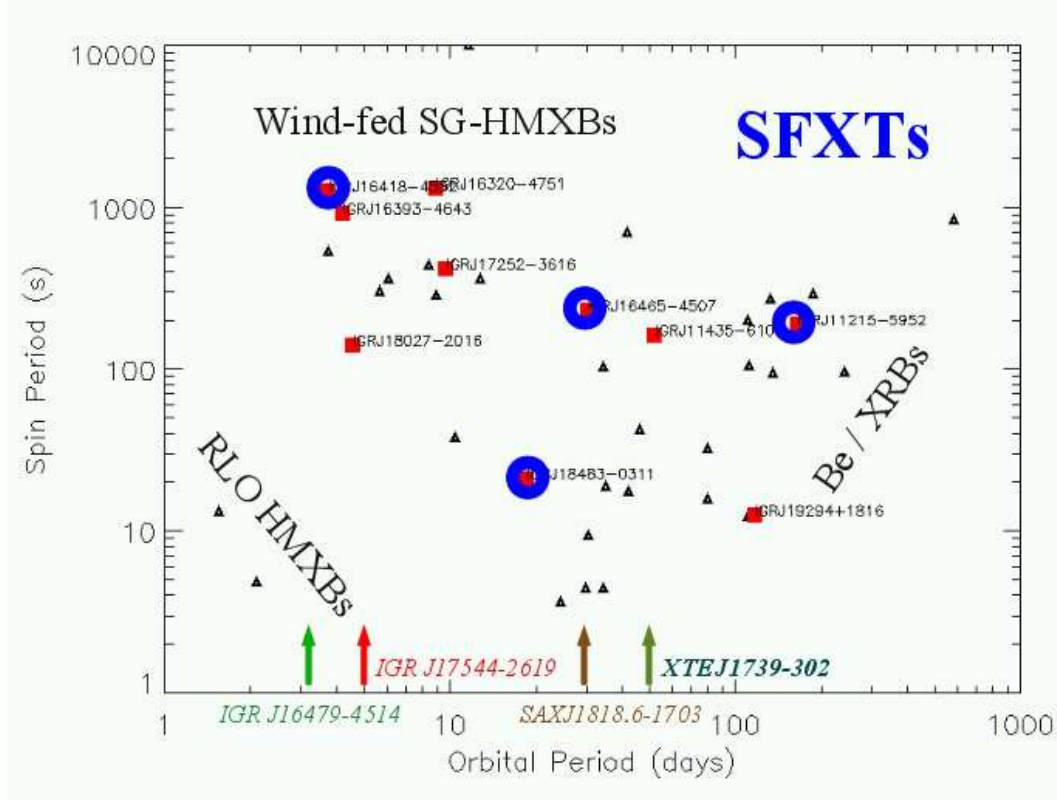


Fig. 1. Corbet diagram of Galactic accreting pulsars, together with the new sources discovered with *INTEGRAL* (red squares), and a few SFXTs where both spin and orbital periods are known (blue circles). On the orbital period axis, the position of other four SFXTs have been marked, for which the spin periodicities are still unknown.

ted in the Corbet diagram of all known Galactic high mass X-ray pulsators (Fig. 1), where three different loci were originally recognized (Corbet 1986): Be-star binaries (where spin periods are correlated with orbital periods), supergiant systems with long spin periods ($\sim 100-1000$ s; wind-fed HMXBs) and narrow orbits ($P_{orb} \sim 10$ days) and supergiant systems with shorter spin periods ($\sim 1-10$ s; Roche lobe overflow, disk-fed systems). One of the puzzling facts about the new supergiant HMXBs discovered with *INTEGRAL* is that some SFXTs lie in the region typical for Be/X-ray transients (like IGR J11215–5952) or in an intermediate region of the Corbet diagram (like in the case of IGR J18483–0311), in a sort of *bridge* between the two main loci of OB supergiants and Be donors. It has been suggested that the SFXTs lying in the Be/XRBs region of the Corbet diagram are indeed the descendant of these binary systems (Liu et al. 2010, Chaty 2010). Interestingly, IGR J18483–0311 shows also an X-ray flaring activity with a higher duty cycle (in excess of 3%) than typically observed from SFXTs (see Fig. 2), possibly indicative of an intermediate system between SFXTs and persistent HMXBs with supergiant companions, as suggested by Rahoui & Chaty (2008). The other source with a high hard X-ray duty cycle is IGR J16479–4514 (2.7%), with an unknown spin period, while IGR J11215–5952 has a small duty cycle of 0.3-0.6%. A

sensitive Swift/XRT monitoring of IGR J18483–0311 along an entire orbital period caught this SFXT almost always active, except during a specific orbital phase, probably because of an X-ray eclipse or a gate mechanism (Romano et al. 2010). The source light curve was highly variable, with several flares, with an average X-ray luminosity probably modulated by the orbital period, likely because of an eccentric orbit ($e \sim 0.4$, Romano et al. 2010). Thus, it is also possible that a continuum of behavior exists between the persistent supergiant HMXBs and the SFXTs with very rare X-ray activity. To date the SFXTs duty cycles observed at hard X-rays (> 20 keV) are typically small (Fig.2) and highly variable from source to source. Considering *INTEGRAL* observations of bright flaring activity, the percentage of time spent in flares with respect to the total observing time of the source field can vary between 0.05% and 3-4% (for SFXTs in the central region of our Galaxy, after 7 years of observations with *INTEGRAL*; Ducci et al., 2010).

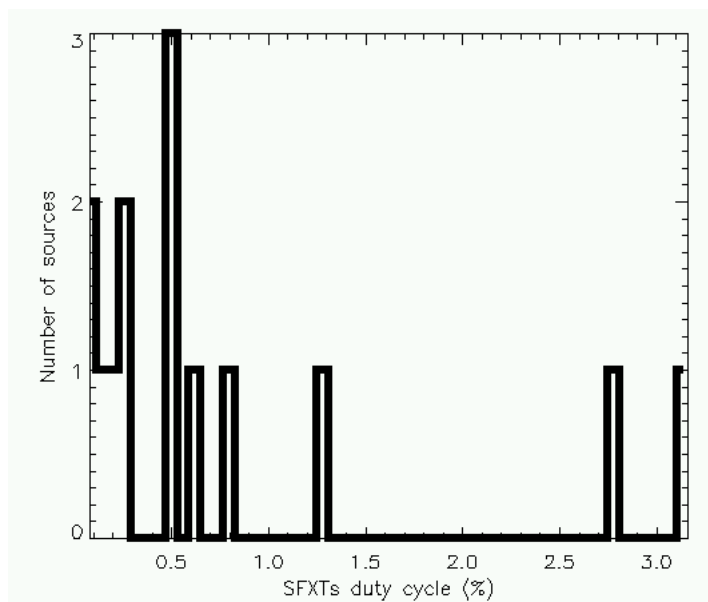


Fig. 2. Histogram of the SFXTs duty cycles (% of time spent in bright flaring X-ray activity, as observed with *INTEGRAL*; data from Ducci, et al. 2010).

2 Future perspective

Despite the huge amount of observational data, several issues are still open: one of the main problems is related with the link between SFXTs and HMXBs with supergiant companions and persistent X-ray emission. Indeed, these two kind of XRBs have both similar compact objects and donor stars, and in a few cases, also very similar short orbital periods (as in the case of IGR J16479–4514, Jain et al. 2009, and IGR J17544–2619, Clark et al. 2010). So, since in these particular cases, the possibility of different orbital parameters are

very likely ruled out as the main mechanism at the origin of the two different classes, other mechanisms should be at work: either a property of the neutron star (the magnetic field and/or the spin period, as suggested by Grebenev & Sunyaev 2007, Bozzo et al. 2008) or a property of the OB supergiant: a different clumping factor in their strong winds from the supergiant star in persistent HMXBs and in SFXTs, or the presence of a preferential plane for the outflowing wind, inclined with respect to the orbital period in SFXTs, which is crossed by the neutron star producing the SFXTs X-ray flaring activity (Sidoli et al. 2007). Also the ionization effect could play an important role especially in binary systems with narrow orbits (Ducci et al. 2010). To date, none of the different mechanisms proposed for the transient outbursts in SFXTs are able to explain all the observational facts (see Sidoli [2009] for a detailed review).

The possibility of a different accretion mechanism in persistent HMXBs with supergiant donors and in SFXTs is also linked to the open issue of the evolutionary histories of these two subclasses of massive binaries. Their census in our Galaxy, as well as their proper duty cycles, are also open questions. In conclusion, a more sensitive monitoring campaign of the hard X-ray sky is needed, at all timescales, in order to try to answer to all these questions, to discover new periodicities (both spin and orbital periods) and know more about their nature, to accurately model their broad band spectra on the shortest timescale possible, to possibly detect cyclotron lines and measure the neutron star magnetic field. This latter is indeed unknown for *all* SFXTs, except in IGR J18483–0311, where a cyclotron emission line at 3.3 keV has been discovered with *XMM – Newton* indicating a low magnetic field of 3×10^{11} G (Sguera et al. 2010), thus ruling out any magnetar nature for this SFXT.

In the following I will report on simulations of SFXTs in the framework of two X-ray missions perfectly suited to study SFXTs and possibly solve most of their open issues: the Energetic X-ray Imaging Survey Telescope (EXIST, Grindlay et al. 2010) and the New Hard X-ray Mission (NHXM, Tagliaferri et al. 2010).

2.1 EXIST

The high-energy telescope (HET, 5–600 keV) for EXIST was mainly suited to perform a survey of X-ray transients, thanks to its large field of view (70 degrees \times 90 degrees) and an unprecedented sensitivity (the full sky would have been observed in a two year continuous scanning survey), able to detect and quickly localize ($< 20''$) X-ray sources for rapid follow-up. Unfortunately, the Decadal Survey Report on the 13th of August 2010 did not recommend EXIST. On the other hand, a future mission with the EXIST concept is certainly needed to investigate the fast X-ray transient sky.

In Fig. 3 I report a spectrum simulated with HET, with a spectral shape typical for a SFXT at the peak of its outburst, with a short exposure time of 1 ks. The spectral parameters are the following: a 5–100 keV flux of 8×10^{-9} erg cm $^{-2}$ s $^{-1}$, which translates into a net count rate of 2360 ± 9 s (HET, 5–100 keV), assuming a power law photon index of 0.66, a cut-off at 4 keV and an e-folding energy at 15 keV.

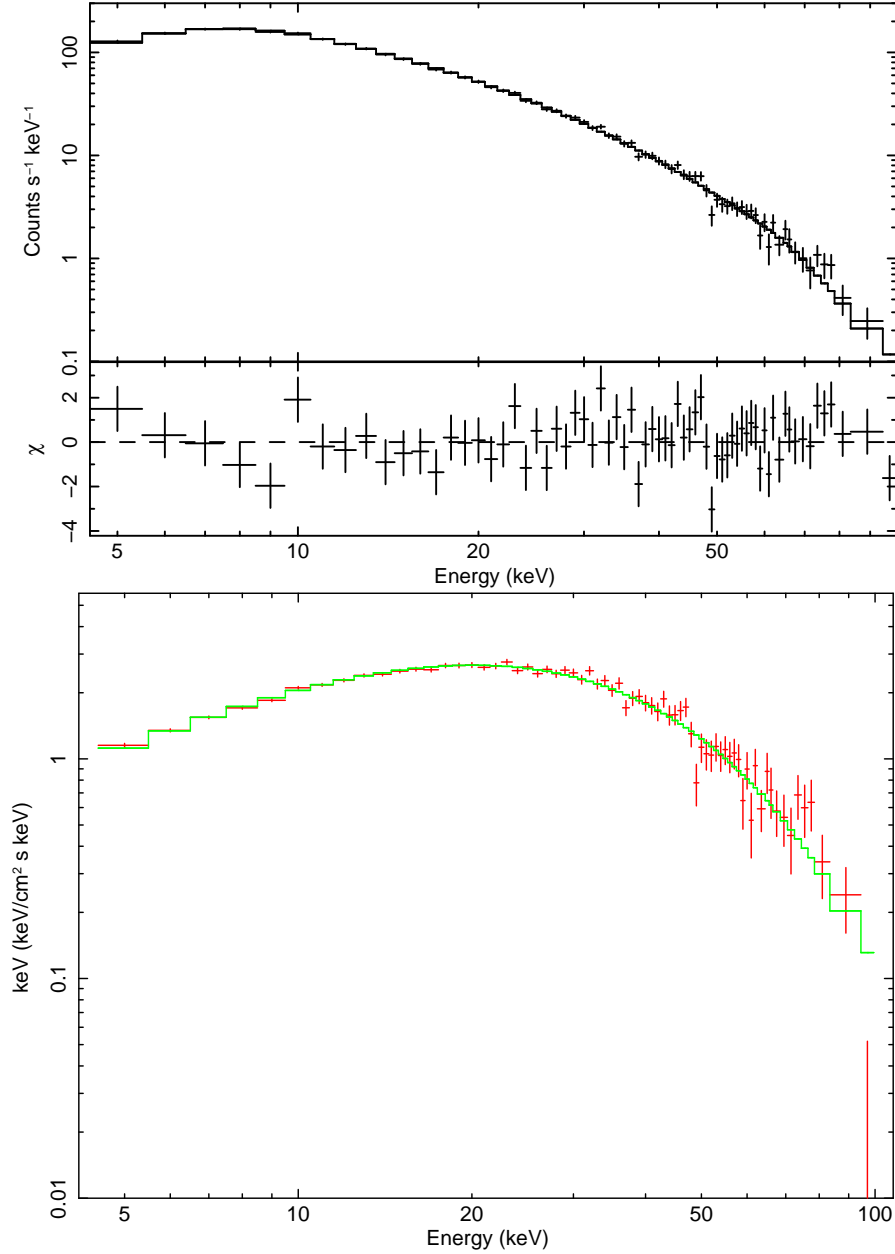


Fig. 3. Simulated spectrum with EXIST/HET (5–100 keV) of a SFXT in outburst ($T_{exp}=1000$ s). *Top panel:* Counts spectrum together with the residuals, in units of standard deviations; *Bottom panel:* Energy spectrum (see text for the spectral parameters).

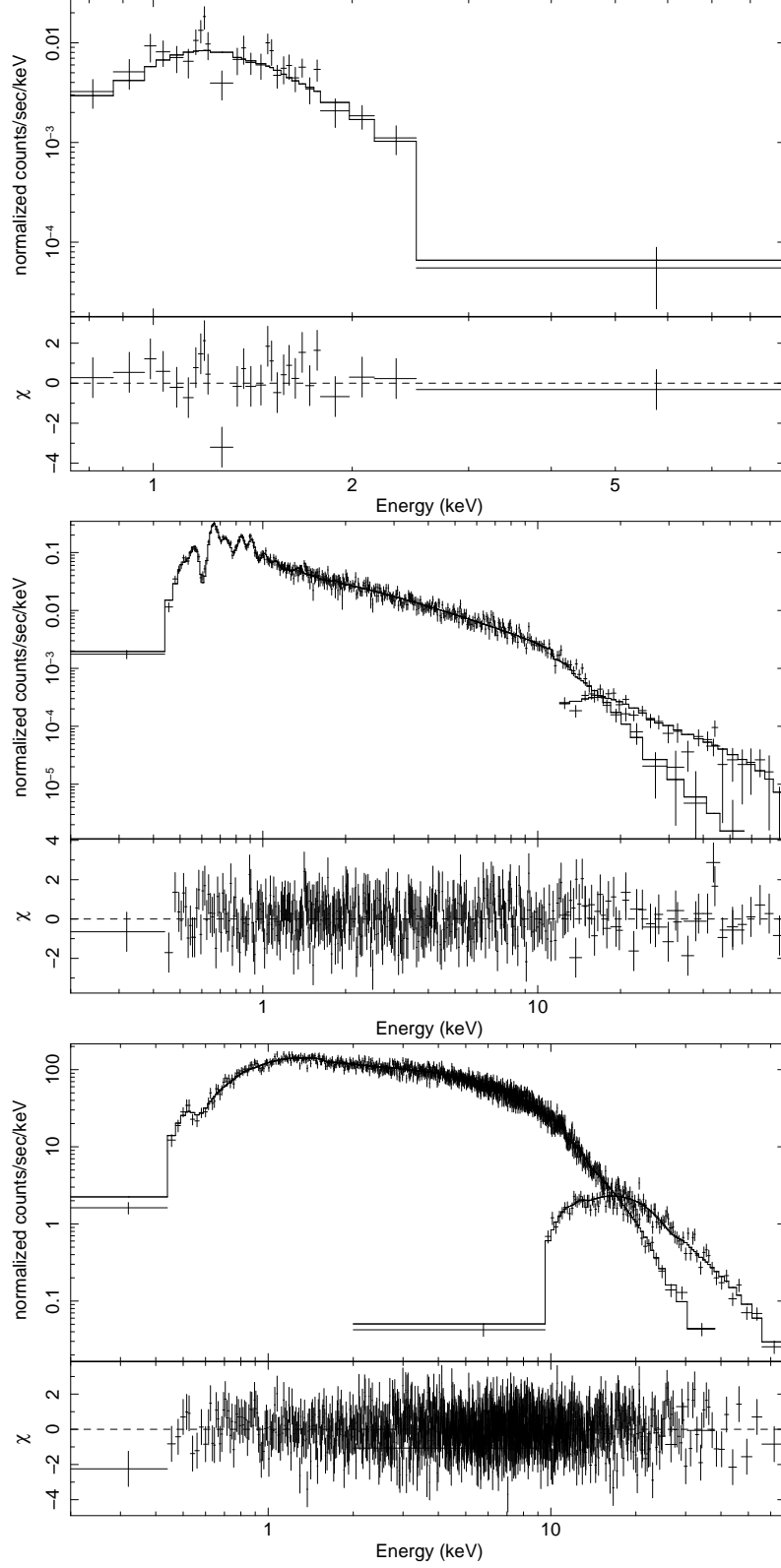


Fig. 4. NHXM simulated broad band spectra of a SFXT in its three intensity states: in quiescence, with a flux of 1.2×10^{-14} erg cm $^{-2}$ s $^{-1}$ (1–10 keV; *Top panel*), in an intermediate level of X-ray emission at 4×10^{-13} erg cm $^{-2}$ s $^{-1}$ (1–10 keV; *Middle panel*), and in bright flaring activity (8×10^{-9} erg cm $^{-2}$ s $^{-1}$, 1–100 keV; *Bottom panel*). See text for details on the spectral parameters.

2.2 NHXM

The New Hard X-ray Mission (NHXM) is a medium size mission proposed for launch in 2016 and designed to gain important insights into several hot astrophysical issues, including the physics of accretion, the study of the highly absorbed and obscured sources, and allowing to resolve the hard X-ray background.

NHXM will be able to obtain imaging and spectroscopic capability in the energy range 0.2–80 keV, together with sensitive photoelectric imaging polarimetry. It consists of four identical mirrors (the X-ray polarimeter is at the focus of one of these telescopes), with a 10 meters focal length, achieved thanks to a deployable structure. A low background will be obtained thanks to a low equatorial orbit. The field of view is of 12 arcmin, and a Half Power Diameter of 20 arcsec at 30 keV is expected (Tagliaferri et al., 2010).

NHXM high sensitivity is particularly well suited for studying the fast spectral variability from SFXTs. Indeed, their short timescales (from a few hundred second to a few hours) of the bright flaring activity have hampered to date a detailed investigation of their broad band spectral variability during short flares and an in-depth study of the variability of the absorbing material towards the line of sight, coming from the supergiant wind and directly accreting onto the compact object.

A detailed modeling of the broad band spectrum is crucial in this respect, to well constrain the low energy absorption (and its variability) and to obtain physical spectral parameters (temperatures and optical depths of the Comptonizing plasma in the accretion column), instead of using simple phenomenological models (like power law with high energy cutoff). This kind of investigation is essentially limited today by the source fast variability timescale and thus cannot be improved adopting huge exposure times with the present generation of instruments.

The spectral simulations I am reporting in Fig. 4 demonstrate that NHXM will allow to probe the variability of the source properties on short timescales of a few hundred seconds during the outburst phase. In particular, simulations of SFXTs spectra adopting physical models (e.g. Comptonization emission, bulk motion Comptonization model, BMC) with a short exposure time of 100 s, allow already the determination of the spectral parameters with small uncertainties at a level of few %, to be compared with a 200 s exposure of the SFXT IGR J08408–4503 with *Swift*/XRT and BAT, reported in Sidoli et al. (2009), where spectral parameters could be obtained only with an uncertainty at a level of 25% (with a flux corrected for the absorption, in the 1–100 keV range, of 8×10^{-9} erg cm⁻² s⁻¹).

An open issue is also the measurement of the neutron star magnetic field in these sources by means of the detection of a cyclotron absorption line. NHXM, thanks to an accurate modeling of the broad-band continuum, will allow to observe a cyclotron absorption line at 12 keV already with an exposure time of 500 s, if the source is flaring at a flux of $8 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$. Simulating a broad band continuum (hard power law with a high energy cutoff, similar to the IGR J08408–4503, Sidoli et al. 2009) together with a cyclotron line at 12 keV (depth = 0.5; width = 3 keV) and its harmonic (depth = 1; width = 5 keV), it is possible to obtain with NHXM (3 modules) the energy of the fundamental with an uncertainty of 0.8% (90% confidence level). Note that the energy range between 10 and 20 keV is hardly covered by the present generation of instruments.

The actual accretion mechanism can be investigated through the broad band spectroscopy, searching for changes in the absorbing column density. Some of these sources are highly absorbed, other are not, but still there is evidence that the absorbing column density is in excess of that towards the optical counterparts. This excess in the low energy absorption is very likely local to the sources and due to the supergiant wind. The possibility to probe the fast spectral variability on timescales of a few hundred seconds is fundamental in unveiling the accretion mechanism, the structure of the supergiant wind (helping in disentangling anisotropic from spherically symmetric winds), and the interaction between the wind and the compact object.

Another issue is the spectroscopy of the SFXTs intermediate intensity state (10^{33} – $10^{34} \text{ erg s}^{-1}$) and of their quiescence level ($10^{32} \text{ erg s}^{-1}$). In particular, a good quality spectrum of the true quiescence is lacking, and a study of the variability of both source states would be interesting, to better understand the nature of these objects.

Observations with *Chandra* and *XMM – Newton* of a couple of SFXTs seem to indicate that their quiescent spectrum is very soft (power law photon index of 5.9, as in the *Chandra* observation of IGR J17544–2619, in’t Zand 2005). Preliminary simulations of this same model with NHXM demonstrate that, with an exposure time of 100 ks, it is possible to perform a good spectroscopy of the quiescent spectrum below 10 keV, finally distinguishing a featureless power law-like spectrum from a hot plasma model (MEKAL model in XSPEC, see Fig. 4, top panel, F_X (1–10 keV) = $1.2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$, $N_H = 1.4 \times 10^{22} \text{ cm}^{-2}$). The spectroscopy of SFXTs at hard energies (above 20 keV) is possible to date only during bright outbursts. NHXM will allow to perform spectroscopy of SFXTs also during their intermediate intensity state (see Fig. 4, middle panel, for a simulation of a SFXT with the same spectral shape observed with *Suzaku* from IGR J08408–4503 by Sidoli et al. (2010), with an exposure time of 100 ks at a flux level of F_X (1–10 keV) = $4 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$).

In conclusion, NHXM sensitivity will allow to really follow the evolution of both the spectrum and the absorbing column density in SFXTs, probing directly both the accretion process and the structure of the supergiant wind, during each single bright flare (a few hour long). These issues are expected to remain unsolved for years, since these questions need to be answered by a much higher sensitivity than the present instrumentation, to follow the rapid source variability.

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